3D CORONAL STRUCTURES FORMATION IN A KINETIC APPROACH: TRANSIENTS AND RAYS

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Abstract

The dynamical Solar corona in 3D consists of transient type magnetic island elements and radial type magnetic flux rope structures. These elements during formation and relaxation produce inductive e.m. fields generating energetic particles. Beams of energetic particles excite at high frequencies type I and type III radio storms. We study the 3D corona formation in a kinetic approach treating it like a hot current carrying collisionless plasma. As a base for corona modeling we use a 2D diamagnetic model where we have a diamagnetic neutral current sheet (slab disk) submerged into the Solar wind high speed hot plasma flow. According to this diamagnetic approximation and in accordance with Solar wind observations in the vicinity of the sheet, a low speed flow is formed and the particle distribution function is a bimaxwellian (double humped) one and describes a double velocity flow with a relative velocity. On the far periphery of the sheet we have a high speed flow only with a maxwellian distribution function.

There is a set of parameters describing a current carrying plasma and flow in diamagnetic stationary state: the particle gyroradius, velocity, and pressure in the high–velocity flow. The ratio between these parameters is weakly dependent on the radial distance and determines the value and sign of the plasma anisotropy parameter in the system. The anisotropy has a negative sign when the diamagnetic currents have a stronger effect with regard to flows, while it has a positive sign when the flows are stronger.

A 3D dynamical structure of the corona with diamagnetic and resistive currents is treated like a result of relaxation or instability of the 2D initial diamagnetic state due to the excitation of large scale surface type resistive electromagnetic modes. Excited electric fields accelerate plasma particles and are studied with two mutually perpendicular wave vector orientations forming cases of tearing and stratification modes.

For a negative anisotropy sign, we have a tearing mode and for a positive sign there is a stratification mode in the system. The tearing mode characterizes the formation of radially moving transient type magnetic islands while the stratification mode forms radial magnetic ropes or rays. With an increase of the anisotropy value we have a decrease of the scale of the structures. When there is a balance between flow and current and the anisotropy is damped, i.e., under stable conditions,

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the current disk thickness rapidly decreases in the lower corona but then in the interplanetary space its value grows smoothly with radius in accordance with the dynamics of the Solar wind flow.

1 Introduction

Observations and concepts of quasistationary coronal structures (QCS) for the simplest case when there is a period of the Solar activity minimum show that a coronal structure is a formation with increased density of a low velocity Solar wind plasma flow surrounded by a high velocity wind flow with a decreased plasma concentration. The main peculiarity of QCS is the existence of magnetic field lines closed on the Sun surface in the lower corona and field lines are open in the interplanetary space (r, θ dependence) in the upper corona part [Hundhausen, 1972]. Ray structures (θ, ϕ dependence) above the closed ones in the open regions also exist. Closed magnetic field lines are associated with magnetic islands or transients. Ray structures are associated with magnetic flux tubes and streamers. The above peculiarities of the corona structure determining its three–dimensional (3D) character will be called a corona *fine structure* and is optically often observed (Figure 1).

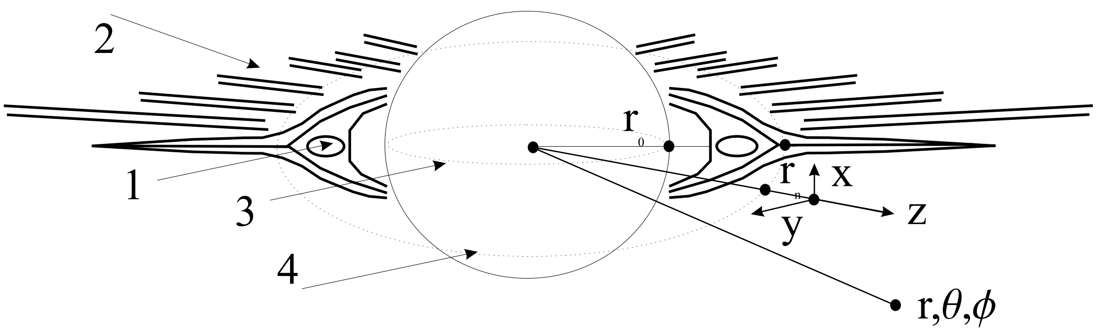

Figure 1: A 3D view of Solar corona out of ecliptic plane during its minimum with fine structure elements. Here x, y, z defines the Cartesian coordinate system located in the ecliptic plane, r, θ, ϕ are spherical coordinates, and r_0 is the Sun radius. 1: It is a circular region of closed magnetic structures with a set of magnetic islands – transients excitation, 2: This is a circular region of open magnetic field lines with rays, magnetic ropes elements, streamers, 3: A circle with Sun radius r_0 in the ecliptic plane where active regions are located. 4: A circle border with radius r_n in the ecliptic plane where the transition from magnetic islands to magnetic rope structures takes place.

The main factor leading to the appearance of corona structures is the combined action of two physically different types of sources: A source of a dipole/toroidal–type magnetic field located in the Solar interior and a source of the Solar wind high velocity plasma. As a result, we observe a formation of dissipative QCS with a complex distribution of quasistationary (inductive) electromagnetic fields (QEM), velocity fields (including low velocity and high–velocity plasma flows), diamagnetic and resistive electric currents and respective density distributions.

QCS are characterized by energy dissipation (relaxation) in sources mainly due to collisionless kinetic mechanisms of relaxation through the acceleration work of QEM fields under resonance with some charged particles of different species α. This dissipation/acceleration provides magnetic reconnection which radically changes the initial magnetic topology of the sample diamagnetic field. The process is accompanied by radio noise type I and III storm activity [Trottet et al., 1982].

QCS are complex global three–dimensional (3D) dynamic formations which can be described while solving the kinetic equations. Normally they are treated in MHD and the kinetic approach is used only for microscale high frequency modeling [Feldman, 1979]. Here in hot collisionless plasma corona, the plasma conditions $u_w \ll v_e, v_i$ are fulfilled, where u_w is the velocity of the corona expansion, $v_{i,e}$ are the thermal velocities. In this case only some resonant particles in the core of the particle distribution function $f_\alpha(\mathbf{v})$ take part in the formation of the resistive fine structures of the corona, so the large scale kinetic approach (not MHD) via inductive type modes application is an adequate task of corona modeling. The evidence of kinetic process in the corona can be found from measuring of nonmaxwellian particle distribution functions in the Solar wind and from theoretical estimations [Schwenn and Marsch, 1990; Marsch et al., 1982; Lemaire and Sherer, 1971; Meyer–Vernet, 1999].

From the relative stability of these structures, it is reasonable to simplify the task and firstly, analyze the QCS stationary state using a rough diamagnetic model and then, test this state for instability. This approach makes it possible to find out the tendency of the system development into a real three–dimensional fine structure with transient and ray elements and finally to describe the state of the system in its new dissipative equilibrium.

Corona QCS formation can be treated from two limiting points. One point is the result of 2D magnetic dipole diamagnetic structure expansion into a 3D current disk due to pressure anisotropy development in dipole and subsequent resistive electromagnetic (e.m.) instability development in a magnetic dipole structure loaded by a current–carrying plasma. The other point is the result of evolution through resistive currents of a slab 1D diamagnetic current sheet with radial field lines [Parker, 1963]. Both of these approaches finally must yield similar results on the corona structure.

Stability tests of stationary states can be carried out successively only when the states are rather simple in construction, at best when they are quasi 1D. For our case, we treat a quasi–one–dimensional current disk modeling a rough QCS structure as more preferable (Figure 2).

QCS with a fine structure of fields are then the result of the evolution of a neutral current disk surrounding the Sun. It is convenient to describe this disk (for the case of sufficiently thin sheets) using a model of a neutral current sheet (CS).

The evolution of the disk is caused by the excitation of modes in QEM fields or, in other words, by excitation of Weibel–type e.m. modes which (for the case of a neutral sheet) transform into a tearing mode describing closed and opened structures with transients

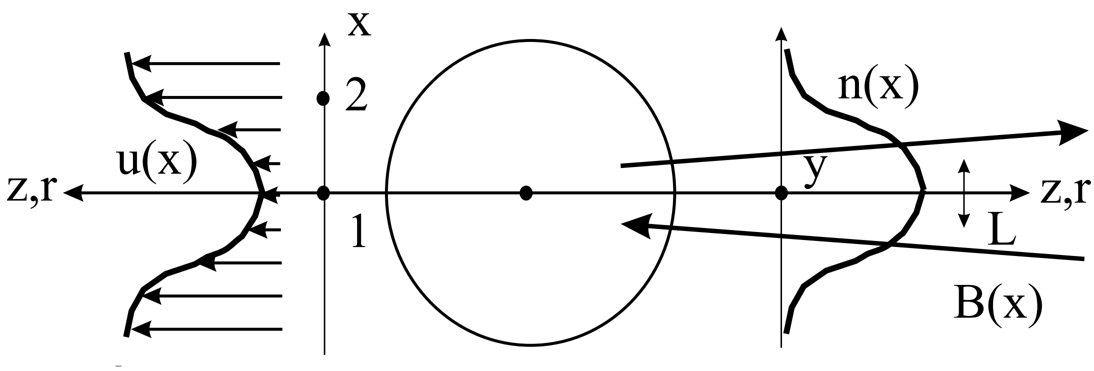

Figure 2: A Solar corona in rough 2D approximation by a neutral current sheet which is submerged into a high speed Solar wind flow. On the left side of the figure is a velocity profile $\mathbf{u}(x)$*, region 1 is a low speed flow and region 2 is a high speed flow. On the right side is the profile* $n(x)$ *of the plasma density with maximum at the neutral sheet where the radial magnetic field* $\mathbf{B}(x)$ *changes its direction and where the current disk is located. Quantity* L *is the neutral current sheet thickness.*

(r, θ) or into its modification, i.e., into a stratification mode describing a ray structure, (r, ϕ) in the corona.

An important factor in modeling coronal structures by a neutral current sheet are plasma flows of the Solar wind which form this CS and support its quasistationary state. A model of a CS with maximum concentration in a plane where the magnetic field changes its direction and reaches zero is adequate to reality. The model has also to describe a low–velocity plasma flow near the neutral plane and high–velocity plasma flows in the periphery of the sheet where the magnetic field reach maximum value. The possibility for a self–consistent description of plasma flows with a bimaxwellian and more complex functions of particle distribution must exist as well.

The modeling of the corona by the above current disc determines a *rough steady structure* of the Solar corona and the interplanetary space. A *fine structure* of the corona appears as a result of the current sheet dynamics on QCS modes. Note, however, that QCS seem to be at the instability threshold and thus, it is possible to describe the state of QCS in more detail using the criteria of instability.

The first part of a paper is devoted to the diamagnetic model of a QCS in a stationary state. The second part of paper is devoted to the stability study of the slab diamagnetic structure and the formation of resistive fine structure elements. The third part deals with the corona fine structure conception.

2 A model of the corona stationary state by a particle distribution function in diamagnetic state

Proceeding from the above requirements to our rough model of the corona structure, let us idealize the stationary state which we treat like a diamagnetic one and represent it as a flat neutral CS submerged in the Solar wind high velocity plasma flow isotropically spreading from the Sun in all directions. The particle distribution function of a neutral CS has the form [Gubchenko, 1982]:

$$f_\alpha = f_{c\alpha} + f_{w\alpha}, \tag{1}$$

where

$$f_{c\alpha} = \frac{n_{c0}}{(2\pi v_\alpha)^{3/2}\cosh^2(x/L)} \times \exp[-\frac{v_x^2 + (v_y - u_\alpha)^2 + (v_z - u_c)^2)}{2v_\alpha^2}],$$

$$f_{w\alpha} = \frac{n_w}{(2\pi v_\alpha)^{3/2}} \exp[-\frac{v_x^2 + v_y^2 + (v_z - u_w)^2)}{2v_\alpha^2}]. \tag{2}$$

Index α marks electron and ion plasma components, u_α is the drift velocity of particles responsible for the current in the system, $v_\alpha^2 = (T_\alpha/m_\alpha)$ is the thermal velocity, T_α is the temperature, m_α is the mass of particles, $v_e^2 = (m_e/m_i)\tau_e^{-1}v_s^2$, $\tau_e = (1 + T_i/T_e)$, v_s is the sound velocity. This distribution function is a generalized Harris [1962] distribution function. Cartesian coordinates are placed at the neutral plane $x = 0$. In this rotating coordinate system the relation

$$u_i T_e + u_e T_i = 0 \tag{3}$$

is fulfilled so that the sheet is not charged, $\mathbf{E}_0 = 0$.
The given distribution function is a bimaxwellian one and describes a double velocity plasma flow in the vicinity of the neutral plane, u_w is the velocity of background plasma, corresponding to a high velocity flow, u_c is the velocity of the CS plasma and its deviation from zero means a possible plasma outflow from closed regions of the magnetic field (Figure 3).

The moments of the distribution function describe the flow

$$\mathbf{u} = \mathbf{e}_z[u_c + \frac{\Delta u \beta_w}{\beta_w + \cosh^{-2}(x/L)}] + \mathbf{e}_y u_\alpha \tag{4}$$

with a small velocity shear and an inhomogeneous profile of the density,

$$n(x) = n_w + n_{c0}\cosh^{-2}(x/L), \tag{5}$$

with its maximum in the neutral plane. At $x \sim 0$ we observe a continuous transition from a low–velocity flow region into a high–velocity one ($\mid x \mid \to \infty$). Note that inside the CS the flow is a double–velocity one with a relative velocity $\Delta u = u_w - u_c$ which does not depend on the transverse coordinate x. We can introduce the dimensionless parameter $\varepsilon_{w\alpha} = (u_w - u_c)/v_\alpha$ which is the value of flow anisotropy.

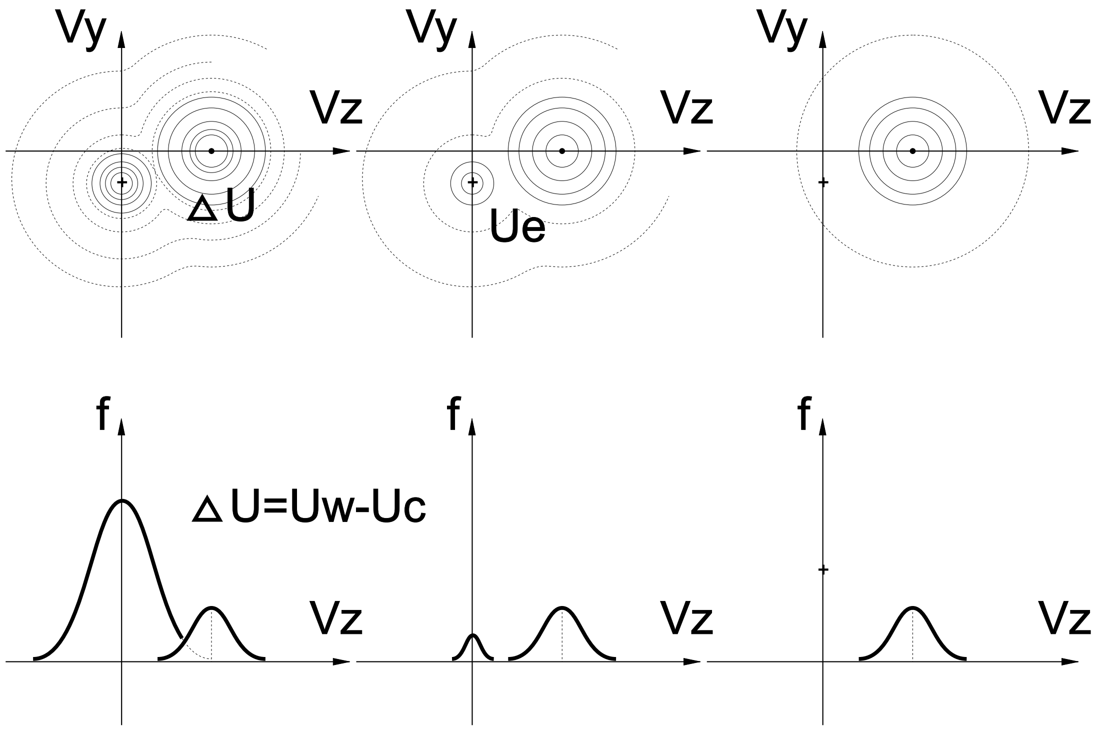

Figure 3: Two dimensional view of the resulting distribution function in a model of the current sheet submerged into high speed flow for points in low speed, intermediate region and high speed. The distribution function coming from observational data for protons and electrons are shown for comparison.

The selfconsistent magnetic field

$$\mathbf{B}_0 = B_w \tanh(x/L)\mathbf{e}_z \tag{6}$$

is connected with the inhomogeneity of the electric current

$$\mathbf{j} = en_{c0}(u_i - u_e)\cosh^{-2}(x/L)\mathbf{e}_y \tag{7}$$

in the system. The condition of the pressure balance $B_w^2/8\pi = n_{c0}(T_e + T_i)$ allows for the matching of the CS plasma state with that of the high velocity periphery plasma. For this matching we must use the plasma parameter $\beta(x) = p/p_m$, where $p = nT_e\tau_e$, $p_m = B^2/8\pi$ in the high velocity flow $\beta = \beta_w = n_w/n_{c0}$.

The relative differential angle rotation of the current sheet relative to the high speed Solar wind plasma can be characterized by the formulas

$$\mathbf{\Omega}_i = u_i \cosh^{-2}(x/L)r^{-1}\mathbf{e}_x. \tag{8}$$

$$\mathbf{\Omega}_e = -u_e \cosh^{-2}(x/L)r^{-1}\mathbf{e}_x. \tag{9}$$

A characteristic inhomogeneity scale L (the sheet thickness) in the diamagnetic state is the magnetic Debye scale r_{DM} in a current carrying plasma. It is determined by the formula [Harris, 1962; Gubchenko et al., 2001]

$$L^{-2} = r_{DM}^2 = \varepsilon^2 \tau_e \omega_{pce}^2 c^{-2}, \tag{10}$$

where $\omega_{pce}^2 = 4\pi e^2 n_{c0}/m_e$ is the plasma electron frequency in the neutral plane, and $\varepsilon_\alpha = 2^{1/2}\rho_{H\alpha}/L = u_\alpha/v_\alpha$ value of the plasma current anisotropy and is the ratio of the thermal particle gyroradius to sheet dimensions, c is the speed of light and we define $\varepsilon = \varepsilon_e$. In our consideration we shall treat a thick CS when $\varepsilon \ll (m_e/m_i)^{1/2}$.

The 1D model considered reflects all local properties of the QCS plasma. A 2D character of the model is reached by introducing rather weak radial, r dependence into the plasma parameters. The 1D state determines a local stationary state so that the pressure $p + p_m$ in the cross section is constant. The possibility of such an approach follows from the quasi–one–dimensional character of QCS under consideration.

It can be seen that the above rough QCS model possesses some free parameters defining its local one–dimensional structure, these parameters being $L, \beta_w, \rho_{H\alpha}$, and $\Delta u = u_w - u_c$. The existing relative velocity Δu is caused by the Solar wind plasma flow u_w and we propose $\Delta u = \delta u_w$ where $\delta \leq 1$. The relative velocity is thus determined by two free parameters u_w and δ. The relation between the above five parameters which is dependent on r determines the local instability of the system with respect to the development of QEM fields and to the formation of the fine structure.

3 Stability analysis of the current sheet submerged in a plasma flow and the problem of the Solar corona fine structure

The modeling of the corona by a neutral CS indicates the rough characteristics of the corona near active regions. Observations point to the existence of some fine peculiarities in this rough structure which are more dynamic formations. Here arises the problem how to describe a quasistationary diamagnetic state. During instability development not only the diamagnetic state is modified thanks to change of the magnetic field, but dissipative current structures are added due to the acceleration of resonant particles by inductive electric field.

We can get ideas about this state, its dynamics and characteristic scales of excited dissipative structures, when considering the stability of the stationary diamagnetic current disk. At the first stage, it seems necessary to solve some initial linear problem explaining the stability of the system, in particular, to separate out regions of local instability and to get characteristic scales of emerging structures and the time of their development. At the second stage, it is possible to turn to quasi–linear and nonlinear problem studies [Gubchenko et al., 2001].

For sake of simplicity, let us turn to the reference system moving radially (with respect to the Solar frame of reference) along the neutral plane with the velocity

$$\mathbf{u}_z = \frac{\mathbf{e}_z(n_w u_w + n_{c0} u_c)}{n_w + n_{c0}}. \tag{11}$$

In this moving reference system, for flows in a neutral sheet, one has

$$n_w u'_w + n_{c0} u'_c = 0. \tag{12}$$

This condition together with the condition $u_i T_e + u_e T_i = 0$ defines a reference system with $\mathbf{u}'_z = 0$ where the problem is considered.

3.1 Nonstationary distribution function

The Fourier–Laplace image of the distribution function $f_\alpha = f_{0\alpha} + f_{1\alpha}$ perturbation (linear in the field $\mathbf{A_1}, \varphi_1$) in the same reference system (with an initial perturbation not taken into account) has the form

$$f_{1\alpha} = \Sigma_\alpha f_{\alpha 1}, \tag{13}$$

where

$$\begin{aligned} f_{\alpha 1} = \frac{e_\alpha}{v_\alpha^2 m_\alpha c} \{ f_{c\alpha}(x) [(A_{1y} u_\alpha - c\varphi_1) + A_{1z} u_c] \\ + f_{w\alpha}[-c\varphi_1 + A_{1z} u_w] \\ + (\omega - k_y u_\alpha - k_z u_c) f_{c\alpha} + (\omega - k_z u_w) f_{w\alpha}) D_\alpha \}, \end{aligned} \tag{14}$$

and

$$D_\alpha = i \int_{-\infty}^{0} d\tau (\mathbf{A}_1 \cdot \mathbf{v} - c\varphi_1) \exp i(\mathbf{k} \cdot \mathbf{v} - \omega)\tau, \tag{15}$$

where $\mathbf{A}_1(x)$ and $\varphi_1(x)$ define the fine structure of the resulting fields

$$\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1 = \mathbf{E}_0 - \nabla\varphi_1 - \frac{1}{c}\frac{\partial \mathbf{A}_1}{\partial t}, \tag{16}$$

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1 = \mathbf{B}_0 + rot\mathbf{A}_1, \tag{17}$$

in the current sheet with flowing plasma, where

$$\begin{aligned} \mathbf{A}_1 = [A_{1x}(x)\mathbf{e}_x + A_{1y}(x)\mathbf{e}_y + A_{1z}(x)\mathbf{e}_z] \exp i(\omega t - k_y y - k_z z), \\ \varphi_1 = \varphi_1(x) \exp i(\omega t - k_y y - k_z z). \end{aligned} \tag{18}$$

Fields $\mathbf{A}, \varphi$ must be transformed during transition to a laboratory coordinate system. The terms in $f_{\alpha 1}$ which are proportional to u_α, u_c, u_w, c characterize a plasma like a current carrying and flowing medium and define a diamagnetic/dielectric type connection between field $\mathbf{B}_1$, $\mathbf{E}_1$ and perturbations. The resonant terms in D_α when $\omega = \mathbf{k} \cdot \mathbf{v}$ produce the dissipative part of the perturbation in $f_{\alpha 1}$.

The integration in D_α is carried out along the particle trajectory in the stationary magnetic field $\mathbf{B} = B_0 \tanh(x/L)\mathbf{e}_z$, where we have two types of particle trajectories magnetized in the region $\mid x \mid >> d_\alpha \sim (\rho_{H\alpha} L)^{1/2}$ and thus unmagnetized mainly in the region $\mid x \mid > d_\alpha$ where they bounce and "collide with elastic walls" at $\mid x \mid = d_\alpha$.

Such a division enables a local approximation in the expansion of the integral D_α when we propose that the fields $\mathbf{A_1}, \varphi_1$ change slowly on the scale of typical particle trajectory oscillations in the sheet.

For unmagnetized particles

$$D_\alpha = (c\varphi_1 - \mathbf{A}_1 \cdot \mathbf{v})\zeta_0, \tag{19}$$

where $\zeta_0 = (\omega - \mathbf{k} \cdot \mathbf{v})^{-1}$ whereas for magnetized ones $k_y v_\perp / \omega_{H\alpha} \ll 1$,

$$\begin{aligned} D_\alpha &= (c\varphi_1 - A_{1z} v_z)\Sigma_n J_n(\xi_{\perp\alpha}) \\ &\times \exp[in(\alpha' - \phi') + (ik_y v_\alpha/\omega_{c\alpha})\sin(\phi' - \alpha')]\zeta_{n\alpha}, \end{aligned} \tag{20}$$

where $J_n(\xi_{\perp\alpha})$ is the Bessel function, $\xi_{\perp\alpha} = k_y v_\alpha/\omega_{c\alpha}$, $n = 0, \pm 1 ...$, $\zeta_{n\alpha} = (\omega - n\omega_{c\alpha} - k_y u_\alpha)^{-1}$ at $\mathbf{k} = k_y \mathbf{e}_y$ and $D_\alpha = -A_{1y} u_{d\alpha} \zeta_0$, $u_{d\alpha} = v_\alpha^2 / 2L\omega_{c\alpha}$ is the particle drift velocity at $\mathbf{k} = k_z \mathbf{e}_z$.

As a result we can calculate momenta of the distribution function $f_{\alpha 1}$, in particular the charge $\rho_1 = \Sigma_\alpha e_\alpha \int f_{1\alpha} d^3 v$ and the current $\mathbf{j}_1 = \Sigma_\alpha e_\alpha \int \mathbf{v} f_{1\alpha} d^3 v$ to substitute them into the Maxwell equations.

3.2 Maxwell equations for field

The plasma under consideration is formed by two plasmas: A current carrying plasma and a flowing plasma and it is a rather complicated system for a mode structure analysis. We have altogether inhomogeneity (L), gyrotropy ($\mathbf{B}_0$) and anisotropy ($u_\alpha, \Delta u = u_w - u_c$).

In a local approximation which we use here, the plasma can be characterized by a local tensor of the dielectric permittivity $\varepsilon_{ij}(\omega, \mathbf{k}, x)$ where all components are nonzero as well as by the conductivity tensor $\sigma_{ij}(\omega, \mathbf{k}, x)$. The dependence on the wave number $\mathbf{k}$ characterizes spatial dispersion in the plasma and it means a non local connection between the current $\mathbf{j}_1$ and the electric field $\mathbf{E}_1$ in the Ohms law $j_i = \sigma_{ij} E_j$.

The modes in the plasma have a complicated polarization and only in some cases the mode structures have TE ($\mathbf{k} \perp \mathbf{E}_1$) and TM ($\mathbf{k} \perp \mathbf{B}_1$) type polarization with possible circular rotations thanks to gyrotropy $\mathbf{B}_0$ (both to the right and to the left) of vectors $\mathbf{E}_1$ and $\mathbf{B}_1$ with the rotation axis along $\mathbf{k}$. The result comes from the solution of the Maxwell differential equations for the field components φ_1 and $\mathbf{A_1}$ with right side terms $\rho_1(\mathbf{A}_1, \varphi_1)$, $\mathbf{j}_1(\mathbf{A}_1, \varphi_1)$.

There are particular important cases of the symmetry $u_i T_e + u_e T_i = 0$ and $u_c n_c + u_w n_w = 0$ with the wave vector $\mathbf{k}$ orientation perpendicular to the axes of anisotropy. The anisotropy axes $\mathbf{e}_z$, $\mathbf{e}_y$ are along vectors $\mathbf{u}_w, \mathbf{u}_\alpha$ and the axis along the vector $\mathbf{B}_0$. For the low frequency band $\omega \ll \omega_{c\alpha}$ which is under study here the tensor ε_{ij} degenerates to a simple form with only diagonal components $\varepsilon_{yy}, \varepsilon_{zz}$, and ε_{xx}. It gives us the possibility to study independently the L potential mode with φ_1 perturbations and two purely electromagnetic modes which are orthogonal to each other TEM_1 and TEM_2 with ($\mathbf{E}, \mathbf{B} \perp \mathbf{k}$) where $\mathbf{j}_1 \parallel \mathbf{A}_1$.

The modes forming fine dissipative structures are localized near the sheet and are a sort of surface modes ($\mathbf{A}_1(x \to \pm\infty) = 0$) in the wave guide formed by the inhomogeneous plasma and magnetic field. The topology of the magnetic field in the structures strongly depends on the character of perturbations. Consider the behavior of perturbations in two limiting cases when we have the TEM polarization of modes: At $k = k_{\parallel} = k_z$ we have a *tearing mode* $\mathbf{A}_1 = A_{1y}\mathbf{e}_y$ [Gubchenko, 1982] determining the radial (r) structure and angular dependence (θ), while at $k = k_{\perp} = k_y$ a *stratification mode* $\mathbf{A}_1 = A_{1z}\mathbf{e}_z$ determines the angular φ, θ dependence [Gubchenko, 1985] (Figure 4). We choose these directions along the axes of plasma anisotropy $\mathbf{e}_z$ and $\mathbf{e}_y$.

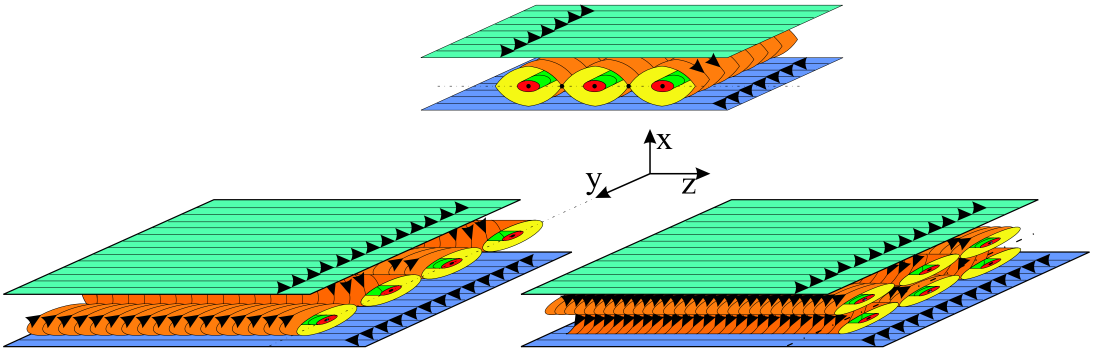

Figure 4: Topology of magnetic field in the current sheet system with excited tearing and stratification mode.

We exclude from the consideration a TEM mode with a $\mathbf{A}_1 = A_{1x}(x)\mathbf{e}_x$ polarization and a wave vector $\mathbf{k} = k_y\mathbf{e}_y + k_z\mathbf{e}_z$ which produce a *"ballerina" type mode* of the heliospheric current sheet, in "our plasma it is stable. Also we don't study the *longitudinal L mode* $\varphi(x)_1$ with $\mathbf{E}_1 = -\nabla\varphi_1 \parallel \mathbf{k}$ which is excited only in case of large anisotropy in the system when the characteristic flow velocities exceed the thermal velocities.

When we introduce an effective anisotropy into any system, for the simplest reference case like a temperature anisotropy $T_{\parallel} \neq T_{\perp}$, we have a Weibel type instability $\gamma(k) > 0$ on TEM inductive modes which appears near small wave numbers $0 < k < r_{DM}^{-1}$ where negative conductivity σ_{ii} is formed [Mikhailovskii, 1974] (Figure 5). The orientation of unstable wave numbers $\mathbf{k}$ is defined by the sign of the parameter of anisotropy $\kappa_\alpha = 1 - (T_{\parallel}/T_{\perp})_\alpha$ forming a diamagnetic scale $r_{DM}^2 = 1/(\Sigma_\alpha \omega_{p\alpha}^2 \kappa_\alpha / c^2)$. During perturbations the plasma behaves here like a diamagnetic media with conductive properties and we have excitation of diamagnetic and resistive currents and structures. If anisotropy κ_α is absent we have a stable plasma.

When anisotropy is formed by the electric current u_α and there is no flow $\Delta u = u_w - u_c$ we have a new $\kappa_\alpha = (u_\alpha/v_\alpha)^2 = \varepsilon_\alpha^2$ [Gubchenko et al., 2001] which is positive and takes into account only currents in the plasma. We have here modifications by magnetization of the Weibel instability profile $\gamma(k)$, with region of unstable wave numbers $0 < k < r_{DM}^{-1}$.

In magnetized region of the plasma for $| x |> d_\alpha$ we have the formation of a dielectric (nonconductive) type of media. The dielectric properties of the plasma in this region are very sensitive to the direction of the wave vector which changes the direction from a quasiparallel regime $\mathbf{k} \parallel \mathbf{B}_0$ with $\mathbf{E_1} \perp \mathbf{B}_0$ to a quasiperpendicular regime $\mathbf{k} \perp \mathbf{B}_0$ with $\mathbf{E}_1 || \mathbf{B_0}$. Conductive properties are localized mainly near the neutral line $| x |< d_\alpha$, where the particles are free to be accelerated by the field. The presence of flows $\Delta u = u_w - u_c$

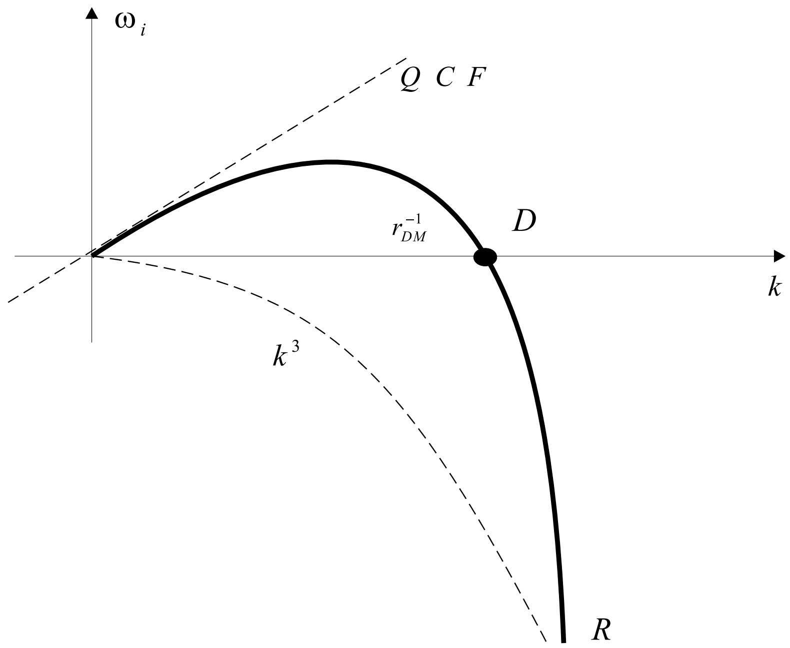

Figure 5: The decay rate $\omega_i(k) = \gamma(k)$ of the TEM mode in an anisotropic plasma in quasi–stationary limit $\omega/kv_\alpha << 1$. The quasi–current–free approximation (dotted line) is valid on the interval $k << r_{DM}^{-1}$ where in the dynamical regime the diamagnetic current j_a is compensated by a current j_r of accelerated particles. The inequality $j_a >> j_r$ holds in the region of stability D where $kr_{DM} = 1$, while $j_r >> j_a$ in region R where the magnetic effects are damped. The dispersion curve of a current–free isotropic plasma is shown by the dotted line in the lower part.

changes the value and sign of κ_α and as a result we have a change of the instability interval and formation of a stable situation with $\kappa_\alpha = 0$. The modified value of $\kappa_{\alpha eff}$ can be found after the solution of the wave equation.

We restrict our study to quasi–static (inductive) $\xi_\alpha = \omega/kv_\alpha << 1$ electromagnetic fields $\mathbf{k} \cdot \mathbf{A}_1 = 0$ in the $\mid \omega \mid \ll \omega_{pe}$ frequency range. Charge perturbations appear only like higher order terms for the terms with small order of $\xi = \omega/kv_\alpha$ that allows for the neglect of the φ field component in the mode. When the inequality $\mid \omega \mid << \omega_{H\alpha}$ is taken into account, A_{y1} and A_{z1} are linearly independent and we get a Maxwell wave equation only for one component of the field A_j

$$\frac{d^2 A_j}{dx^2} - k^2 A_j = \frac{4\pi}{c} j_j(x, A_j), \tag{21}$$

where $j = y, z$.

We restrict to the local approximation of the expression for the currents

$$\begin{aligned} j_j = \Sigma_\alpha e_\alpha \int v_j f_{1\alpha} d^3 v = \\ (\nu_c(\nu_c+1)L^{-2} ch^{-2}(x/L) + \nu_w(\nu_w+1)L^{-2})A_j \\ = \frac{c}{4\pi}\frac{\omega^2}{c^2}\Sigma_\alpha \varepsilon_{jj}^\alpha A_j. \end{aligned} \tag{22}$$

The currents are represented through the dimensionless coefficients ν_c, ν_w depicting a link between the expressions and associated Legendre equation and Legendre functions $P_\nu^{-\mu}[\tanh(x/L)]$ where $\mu = kL$, as well as with the tensor of the dielectric permittivity $\varepsilon_{ij}^{\alpha}(\omega, \mathbf{k}, x)$. The component of the tensor $\varepsilon_{jj}(x)$ is a layered value of x with borders between layers at $\mid x \mid = d_\alpha$, and inside the layer inhomogeneity profile is proportional to $\cosh^{-2}(x/L)$. The real part of $\varepsilon_{jj}(x)$ characterizes diamagnetic perturbations of the plasma and imaginary part characterizes resistive currents in the plasma. As a result we have a waveguide profile for wave equation and we study surface type modes there. The field A_j and its derivatives must be continuous at the boundaries d_α between the layers in the waveguide and this gives us the dispersion equation for a mode.

The expressions for ν_c, ν_w are rather complicated values and are given by Gubchenko [1982] for a tearing mode $k = k_z$, $A = A_{1y}$ and for a stratification mode $k = k_y$, $A = A_{1z}$ in Gubchenko [1985].

The substitution of the variables $\xi = \tanh(x/L)$ transforms the wave equation into the associated Legendre equation with different ν constant and the solutions are matched into boundaries $\mid x \mid = d_\alpha$. Thus we obtain the next dispersion equation for the surface mode

$$\psi_e \varepsilon_e^{1/2} = -\chi_e \tan \chi_e. \tag{23}$$

We introduced the functions $\chi_\alpha = [\nu(\nu+1) - \mu^2]^{1/2} \varepsilon_\alpha^{1/2}$, where $\nu(\nu+1) = \nu_c(\nu_c+1) + \nu_w(\nu_w+1)$ and the function

$$\psi(\nu, \mu, \varepsilon) = \psi_0/[1 + \varepsilon_\alpha^{1/2}\psi], \tag{24}$$

where

$$\begin{aligned}\psi_0 = (P_\nu^{-\mu})'/P_\nu^{-\mu} \mid_{x=0} = -(\nu+\mu)\Gamma(\frac{\nu+\nu}{2}) \\ \times\Gamma(\frac{1+\mu-\nu}{2})/\Gamma(\frac{\mu-\nu}{2})\Gamma(\frac{1+\mu+\nu}{2})\end{aligned} \tag{25}$$

is expressed using the associated Legendre polynomial $P_\nu^{-\mu}(\tanh(x/L))$, the gamma function $\Gamma(z)$, and $\mu = kL$

3.3 Tearing mode

The tearing mode development with $A = A_{1y}$ and $k = k_z$ is governed by the anisotropy of the electron distribution function f_{0e} at a narrow region $|x| < d_e$ where the electrons are unmagnetized and can be accelerated by the electric field E_{1y}. This field easily penetrates into the magnetized waveguide region $|x| > d_e$. For the electron tearing mode we have $\psi_e = \frac{1-\mu^2}{\mu}/(1 + \varepsilon^{1/2}\frac{1-\mu^2}{\mu})$, χ_e is defined by the value of $\nu(\nu+1)$ in the region $\mid x \mid < d_\alpha$. At $M_\alpha = (u_w - u_c)/v_\alpha \ll 1$, where $\mid \chi \mid \ll 1$, the solution of the dispersion equation has the form: The mode phase velocity is

$$v_{ph} = \frac{\omega_r}{k} = \frac{\beta_w}{1+\beta_w}(u_w - u_c) + u_c. \tag{26}$$

This means that the magnetic island structures are drifting upward during the instability development [Gubchenko, 1982]. The instability increment is

$$\xi_e = \frac{\gamma}{2^{1/2} \mid k \mid v_e} = \frac{1}{1+\beta_w}[\xi_H - \frac{1}{\pi^{1/2}}\frac{\beta_w}{1+\beta_w}\frac{(u_w - u_c)^2}{v_c^2}]. \tag{27}$$

Here the first term $\xi_H = \pi^{1/2}\varepsilon^{3/2}\tau_e\psi_e$ describes the instability of the neutral current sheet in case of absence of a flow. The second term with the minus sign describes the stabilization action from plasma flows. It is evident from the expressions that the region $0 < \mu < \mu_*$ of wave numbers where

$$\mu_* = \varepsilon_c^{1/2}(1 - \frac{\varepsilon_w}{\varepsilon_c}) \tag{28}$$

and

$$\varepsilon_w = \tau_e^{-1}\frac{\beta_w}{1+\beta_w}\frac{(u_w - u_c)^2}{v_e^2} \tag{29}$$

is unstable. Thus at $\varepsilon_c > \varepsilon_w$ the flow-current sheet system for the tearing mode is unstable. This result give us the opportunity to define a new value for anisotropy $\kappa_{eff} = \varepsilon_c - \varepsilon_w$. The value ε_w keeps inside not only the flow anisotropy but also the weight in anisotropy of high speed flowing plasma background. Let us note here that the change in flows $\delta u_w = u_w - u_c$ has a stronger effect on the anisotropy in comparison with the change of the current $\delta u = u_i - u_e$.

3.4 Stratification mode

For the stratification mode with field polarization $A = A_{1z}$ and $k = k_y$, we have a nonpenetratable region $|x| < d_e$ for the field and $\psi_c \longrightarrow \infty$. The dispersion equation is transformed into the form $\chi_e = \frac{\pi l}{2}, l = 1, 2, 3, ...$ [Gubchenko, 1985]. The mode is localized to a narrow region $|x| < d_\alpha$ and expands its localization beyond d_α only with a strong increase of M_α. The number l describes modes with different structures, the value of χ_e is determined by $\nu(\nu + 1)$ in the region $\mid x \mid < d_\alpha$. The solution of the dispersion equation at $\Delta u/v_\alpha \ll 1$ has the form

$$v_{ph} = \frac{\omega_r}{k_y} = \frac{\varepsilon_e}{1+\beta_w}u_e \ll u_e, \tag{30}$$

and the instability increment is

$$\frac{\gamma}{2^{1/2} \mid k \mid v_e} = [\frac{\beta_w}{1+\beta_w}(\frac{\Delta u}{v_e})^2\varepsilon_e^{-2}\frac{T_e}{T_i} - \mu^2 - \varepsilon_e^{-1}\frac{\pi l}{2}]/\pi^{1/2}\varepsilon_e^{-2}\tau_e^{-1}v_e. \tag{31}$$

It is thus evident that the region of $0 < \mu < \mu_*$ where

$$\mu_* = \frac{\pi l}{2\varepsilon_e}(\frac{\varepsilon_w}{\varepsilon_c} - 1), \tag{32}$$

$$\varepsilon_w = \frac{\beta_w}{1+\beta_w}(\frac{\Delta u}{v_e})^2 \frac{T_e}{T_i}\frac{2}{\pi l} \tag{33}$$

is unstable. For stabilization we have the opposite case: At $\varepsilon_c < \varepsilon_w$ the stratification mode instability is excited and the flux rope formation takes place. They are in rest because of a relatively small phase velocity. If the inequality is strengthened, there appears the possibility for excitation of modes with finer stratification structures.

4 Concepts of the corona structure transpiring from the theory of current sheet stability

The relation between the free parameters $(L, \rho_{H\alpha}, u_w, \delta, \beta_w)$ characterizes the degree of anisotropy $\kappa_{eff} = \varepsilon_c - \varepsilon_w$ in CS. The system with an anisotropic distribution function is unstable, due to the excitation of QEM Weibel type modes which are highly sensitive to the value and sign of κ_{eff}. At $\kappa_{eff} < 0$, the tearing mode with $\mathbf{A}_1 = A_{1y}(x)\mathbf{e}_y$ and $\mathbf{k} = k_z\mathbf{e}_z$ is unstable. This mode determines the fine structure over θ and r in the sheet with magnetic islands and regions of reconnection. At $\kappa_{eff} > 0$, the mode with $\mathbf{A}_1 = A_{1z}(x)\mathbf{e}_z$ and $\mathbf{k} = k_y\mathbf{e}_y$ is unstable. This is the stratification mode determining the fine structure over φ and θ in the sheet.

The above criteria of the CS instability as well as conditions for its equilibrium allow for the analysis of QCS observed in the corona. These QCS seem to be long living, i.e., they are in state $\kappa_{eff} \approx 0$. This condition presupposes the sheet thickness to be determined by free plasma parameters of the high velocity flow and by the value of δ so that

$$L(r) = \rho_{He}(r)\frac{1+\beta_w}{\beta_w}\frac{1}{\delta^2}(\frac{v_e}{u_w(r)})^2. \tag{34}$$

High speed flow of Solar wind $u_w(r)$ forms in open magnetic field structures. This flow can be treated like an ambipolar outflow of quasineutral hot collisionless plasma in kinetic, two fluid and one fluid MHD [Meyer–Vernet, 1999]. These model can be loaded by additional factors (turbulent heating, etc.) to tune models for fitting observations.

For the simplest case of an isothermal corona in the hydrodynamic Parker model, the free parameters turn out to be linked with the flow parameters at the $r = r_c = 6r_0$ level at $T = 10^6$. At this level the velocity of flows reaches that of the sound v_s [Parker, 1963]. In this model

$$\rho_{He}(r) = \rho_H(r_s)(r/r_s)^2, \tag{35}$$

$$\beta_w(r) = \beta_w(r_s)(v_e/u_w(r))(r/r_s)^2 \tag{36}$$

at $r < r_s$

$$\frac{u_w}{u_s} = \frac{r_s}{r}\exp[-2r_s(\frac{1}{r} - \frac{1}{r_s})], \tag{37}$$

at $r \gg r_s$

$$\frac{u_w}{u_s} = 2\ln(\frac{r}{r_s}), \tag{38}$$

where $L_s = L(r_s)$. After substitution into (34) we have

$$L(r) = L_s \frac{v_s}{u_w} \frac{1 + \beta_w(r)}{1 + \beta_w(r_s)} \frac{\delta^2(r_s)}{\delta^2(r)}, \tag{39}$$

where $L_s = L(r_s)$.
Let $\delta \sim const$, then at $r < r_s$ when $\beta \ll 1$, the sheet thickness decreases exponentially quickly. At $r \gg r_s$ and also in the interplanetary space, at $\beta \sim 1$ the value L smoothly increases according to the power law. This behavior qualitatively corresponds to the behavior of the thickness in the observed QCS. However, in real QCS, the value L varies much more slowly. At $r < r_n = 2r_0$ the QCS is more thin, i.e., $\kappa_{eff} < 0$, but at $r > r_n$ it is thicker and $\kappa_{eff} < 0$. In this case, in lower QCS layers, there emerge conditions for the excitation of the tearing mode, i.e., for reconnection and for the formation of closed structures and magnetic islands. In the upper layers, the tearing mode is stabilized and we find the conditions for the development of the stratification mode which are responsible for the ray structure in QCS. The value of δ probably changes and a new $L(r)$ profile appears.

5 Conclusion

Our consideration is a new attempt to treat the Solar wind (the Solar corona expansion) and the Solar magnetic field together with a complicated large scale dynamical fine structure elements (transients and rays) from the point of pure kinetic theory and to describe the object like a laminar dissipative flow. We don't consider a "noise" approach here which takes into account subsequent quasilinear or nonlinear modification to a given laminar theory we don't add some external noise to the theory which gives the required collision frequency for plasma conductivity formation. We connect dissipation in the laminar system with the acceleration of electrons and ions by an electric field produced mainly by inductive process. This is a basic process in space plasma physics [Treumann and Baumjohann, 1997].

The model is based on the solution of the Vlasov kinetic equation near a 2D stationary diamagnetic state described by a distribution function of a particular type $f_{0\alpha} = f(H_\alpha, P_{y\alpha}, P_{z\alpha})$ formed like a function of integrals of motion, where $H_\alpha = m_\alpha v^2/2 + e_\alpha \varphi$ is the particle energy, $P_{y\alpha} = m_\alpha v + (e_\alpha/c)A_y$, $P_{z\alpha} = m_\alpha v_z$ is the momentum of the particle in the 1D diamagnetic configuration. The diamagnetic background is a base for our analysis to be due to the presence in the corona of huge volumes of a nondissipative hot current carrying collisionless plasma. Dissipative effects are treated like perturbations on a diamagnetic background and as a result the real distribution function f_α of the Solar corona can not be treated like a function of integrals of motion $f_{0\alpha}$.

The plasma is characterized by standard parameters like density n_α and temperature T_α via inclusion of the factor H_α. The diamagnetic plasma is characterized via the factor $P_{y\alpha}$ like a current carrying plasma by an additional parameter $\Delta u = u_i - u_e$ which is the relative drift velocity of electrons and ions. We obtain flowing plasma with difference of fast u_w and slow u_c flow velocities $\delta u_w = u_w - u_c$ via inclusion of factor P_z. The set of plasma parameters of the stationary state define a plasma spatial dispersion r_{sd} which scales the dissipative and diamagnetic (polarization) nature and the value of anisotropy κ_{eff}. The scales are included in the description of the structure of fields of a hot coronal collisionless plasma in its dynamics.

We have not only spatial dispersion parameters of the resting plasma like the nondissipative electric Debye scale r_{DE} and some others (including dissipative) which can be formed from parameters n_0 and T and are used for the ambipolar description of the coronal expansion with potential fields φ formation. We have also a diamagnetic (nondissipative) parameter $r_{DM} = [\Sigma_\alpha(\omega_{p\alpha}/c)^2(u_\alpha/v_\alpha)^2]^{-1/2}$ for the description of Solar corona expansion with a vortex (curl) type field $\mathbf{A}$ formation.

When we are in a stationary state $r_{DM} = L$, and so r_{DM} was invented in plasma physics by Harris [1962], but in a dynamical state during the formation of dissipative structures, we are in a regime that some scales $L \neq r_{DM}$. Normally for weak currents, $\varepsilon_\alpha = \Delta u/v_\alpha \ll 1$, so that we have $r_{DE} \ll r_{DM}$. Due to the small value of Δu and the lack of huge volumes L_p^3 of a laboratory plasma, $r_{DE} \ll L_p \ll r_{DM}$, we observe diamagnetic properties only in space conditions (Earth magnetosphere and Solar corona with heliospheric current sheet) where we have huge volumes of plasma L_p^3 easily $L_p \gg r_{DM} \gg r_{DE}$.

The dimensionless parameters for the classification of the diamagnetic state are the Debye numbers $D_E = L_p/r_{DE}$ and $D_M = L_p/r_{DM}$. We have here $D_E \gg D_M \gg 1$. The limit $D_E \gg 1$ we call quasi neutrality (QN) limit with charge $\rho(\mathbf{x}, t) \sim 0$, the case $D_M \gg 1$ we can call the quasi current free (QCF)is a limit $\mathbf{j}(\mathbf{x}, \mathbf{t}) \sim 0$ or the quasi constant current (QCC) limit, $\mathbf{j}(\mathbf{x}, t) \sim \mathbf{j}_0$.

In a QCF and a QN regime which is realized in space plasma, we have only regions with no QCF at discontinuities (current sheets) with scales where $L \sim r_{DM}$. These discontinuities can be stable or unstable to form inside dissipative structures in form of magnetic islands like transients or magnetic flux ropes like rays with scales in the discontinuity $l >> r_{DM}$.

The model presented is of qualitative nature and allows for the explanation of QCS peculiarities (the behavior of thickness, spatial separation of the field closed structures from ray structures). It starts from the simple concept of a neutral current sheet submerged into the plasma flow. However, some factors hindering the consideration (new type of modes nonlinearity, quasilinear relaxation, temperature anisotropy, collisions, inhomogeneities, a normal magnetic component in CS etc.) which are studied in details in the case of Earth magnetosphere, has not been taken into account here. They evidently demand exists for further analysis.

Acknowledgements: This work was supported by the Russian Foundation of Fundamental Researches, Grant No 99–02–18244. Part of this work was done while V.M.G. was on a research visit to the Space Research Institute of the Austrian Academy of Sciences in Graz and thus we acknowledge support by the Austrian Academy of Science, "Verwaltungsstelle für Auslandsbeziehungen". This work is supported by the INTAS–ESA project 99–01277 and by the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" under project P13804–TPH.

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